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RADAR OBSERVATIONS OF THE EFFECTS OF CHANGING ELECTRIC FIELDS ON THE ORIENTATIONS OF HYDROMETEORS

James I. Metcalf

14 May 1992

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FOR THE COMMANDER

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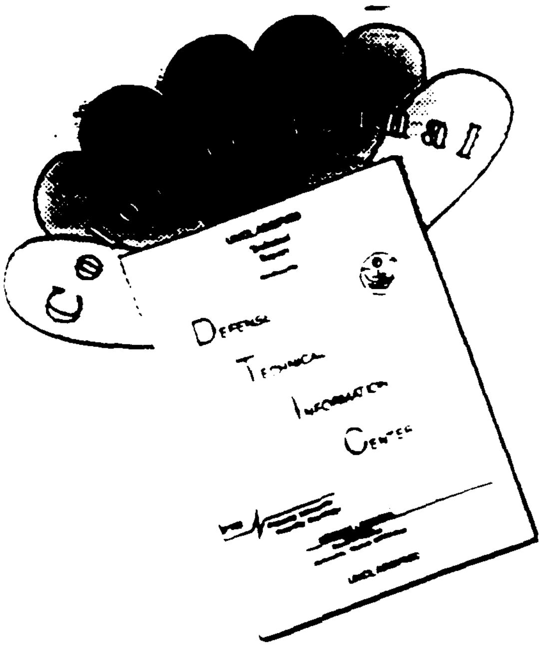

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13. ABSTRACT *(Maximum 200 words)* The changing orientations of hydrometeors due to rapidly changing electric fields in clouds have been observed for the first time at a radar wavelength of 11 cm (S-band) with the polarimetric Doppler radar operated in Sudbury, MA by the Geophysics Directorate of Phillips Laboratory. During 1991 the radar was operated in a half-matrix mode, transmitting a signal of right circular polarization and receiving signals of right and left circular polarization. Observations of electrified storms on nine days during the spring and summer of 1991 revealed several occurrences of lightning that coincided with significant changes of the circular depolarization ratio (CDR), the cross-correlation, or the phase of the cross-covariance of the two received signals. We observed changes up to 2 dB in CDR, 50% in cross-correlation, and 40° in phase. However, many occurrences of lightning observed by radar were not accompanied by detectable changes of hydrometeor orientations, and we did not observe the cyclical changes of the polarimetric quantities that have been observed elsewhere with radars of shorter wavelength. We present examples of our observations and discuss implications for future measurements with this radar.

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Preface

This report summarizes observations during 1991 by the 11-cm (S-band) polarimetric Doppler radar operated by the Ground Based Remote Sensing Branch of the Geophysics Directorate. Many people contributed substantially to the operation of the radar and associated equipment. I am particularly grateful to Master Sergeant Richard Chanley, USAF (Ret.), and to Mr. Timothy Hiett for their support of radar operations during evenings and on weekends. Mr. Pio Petrocchi developed and maintains the antenna control software that is essential to these operations; he also provided valuable assistance in the data analysis. A key factor in the observation of lightning and its effects on hydrometeors is the identification of electrically active regions in real time. This capability is made possible by the combined efforts of Dr. H. Albert Brown of the Atmospheric Structure Branch, who receives the lightning data from the nationwide network; Mr. Charles Ivaldi and Mr. Joseph Doherty of Atmospheric and Environmental Research, Inc. (AER), who are responsible for transferring the data into the Air Force Interactive Meteorological System (AIMS) computer operated by the Satellite Meteorology Branch; and Mr. Frank Ruggiero of the Atmospheric Prediction Branch, who developed software to extract the data from AIMS and transfer the data to the field site. I am grateful to all of them. I appreciate the patience and insight of Prof. Paul Krehbiel of the New Mexico Institute of Mining and Technology, with whom I have discussed our observations and results in considerable detail. Finally, I deeply appreciate the strong support I have received from Mr. Kenneth Glover, Chief of the Ground Based Remote Sensing Branch, at every stage of this work.

Radar Observations of the Effects of Changing Electric Fields on the Orientations of Hydrometeors

1. INTRODUCTION

The 11-cm wavelength (S-band) Doppler radar operated by the Geophysics Directorate in Sudbury, Mass.,[1, 2] has been used since February 1991 in an intensive campaign to measure polarimetric characteristics of backscatter from electrified storms. The principal purpose of these observations is to investigate the changing orientations of hydrometeors in response to changing electric fields in clouds. Similar observations by radars of shorter wavelength elsewhere were reported by Hendry and McCormick,[3] by Hendry *et al.*,[4] and recently by Krehbiel *et al.*[5, 6] Several of these measurements were reviewed by Metcalf.[7] Our specific objectives are to develop and refine observational techniques and to document the variability of the quantities measurable by 11-cm radar. This report presents our most significant observations during 1991.

(Received for publication 14 May 1992)
(The list of references begins on page 29)

The radar is capable of operating in a full-matrix mode, in which it transmits successive pulses with alternating polarization (either horizontal and vertical or right and left circular) and receives signals with polarizations identical and orthogonal to that of the transmitted signal. During 1991 it was operated in a half-matrix mode, transmitting right circular polarization and receiving right and left circular polarizations. The cross-covariance of the two oppositely polarized signals yields the cross-correlation, which is related to the degree of common orientation of the particles, and a phase angle, which is related to the mean apparent canting angle of the particles.

2. OBSERVATIONAL PROCEDURES

During 1991 we operated the radar on most of the days during which precipitation occurred within our surveillance area. We operated the radar on 9 days on which thunder was reported in the nearby synoptic weather observations or on which the nationwide lightning detection network operated by Geomet Data Services, Inc. (originally by the State University of New York at Albany),[8] recorded lightning within our surveillance area. Initially we had access to data from the lightning detection network only through archives at Hanscom Air Force Base, but in May 1991 we implemented a capability to display these data at our field site within a few minutes of real time.

Our observational procedure is as follows. We operate the radar initially in a surveillance mode to determine the locations and movement of precipitation cells. We use the lightning locations from the nationwide network to identify the electrically most active regions. We then observe one of these regions more closely, typically by scanning it first in elevation and then directing the radar beam into the upper part of the storm for several minutes. We set the 50 selectable gates in which the polarimetric data are sampled to span the range domain of interest, and we display the logarithmic received power from either channel on an oscilloscope, as an "A-scope" display. While the antenna is held fixed, we record the polarimetric data and note the the times at which lightning channels intersect the radar beam. These events appear as momentary (typically a few tenths of a second) enhancements of the signal displayed on the A-

scope. After several minutes of observation, we either attempt to follow the center of electrical activity by moving the antenna a few degrees or return to a surveillance mode to establish new parameters for a subsequent observation. On one occasion we scanned a 4-degree elevation sector repeatedly for about 20 minutes in an attempt to observe the spatial distribution of the orientation effects. We expect to conduct more observations of this type in 1992.

After the observations, we examine in detail short segments of the polarimetric data near the times when lightning was observed. In particular, we look for abrupt changes of the circular depolarization ratio (CDR), the cross-correlation, and the phase of the cross-covariance that coincide with the occurence of lightning. Such changes are due to rapid reorientations of hydrometeors by the rapidly changing electric field, which can change their apparent shape, their apparent canting angle, or both. Changes in the measured quantities may indicate either an increase, a decrease, or a change in direction of the electric field.

Our observations during 1991 are summarized in Table 1, which includes all days on which we operated the radar. Those days on which we observed many lightning events are described in more detail in the following section.

3. OBSERVATIONS

3.1. 17 May 1991

A line of convective cells passed through the surveillance area during the afternoon and early evening. From 1530–1700 EST the leading edge of the line advanced from the northwest at about 60 km hr^{-1}. Movement of individual cells within the line was nearly due east. Figure 1 shows lightning recorded by the nationwide network as the line approached the radar. The first polarimetric data were recorded from 1559–1612, when the leading edge of the line was about 100 km distant, at an azimuth of 294° and elevation angle of 2° with range gates set between 85 and 145 km. Cloud-to-ground strikes were widespread along the convective line during this interval; strikes were occurring at a rate of about 5 per minute within

Table 1. Summary of Polarimetric Radar Operations During Spring and Summer, 1991. "Duration" denotes the period during which reflectivity and Doppler mean velocity were recorded continuously. "Time series" denotes the total duration of polarimetric data recorded on tape. "Lightning" denotes the number of lightning events recorded from the A-scope. Polarimetric operations on days without lightning were conducted for cloud microphysical studies or radar system evaluation; these usually included elevation scans or observations at high elevation angles.

Date	Duration (EST)	Time Series (minutes)	Lightning	Description
23 Mar	1400–2032	10	3	Convective cells in vicinity
29–30 Mar	2149–0040	15	0	Widespread showers
2 Apr	1450–1705	27	0	Weak convective cells nearby
5 Apr	1900–1930	17	0	Widespread showers
10 Apr	1754–2116	57	1	Weak convective cells
15 Apr	1320–1542	34	0	Light to moderate rain
21 Apr	0959–1301	17	0	Moderate to heavy rain
30 Apr	0719–1223	46	0	Light rain
1–2 May	2016–0019	16	0	Thunderstorms west, distant
6 May	1419–2312	4	0	Elevation scan in light rain
17 May	1530–2104	76	74	Line of convective cells passed radar
30 May	1446–2017	11	23	Widespread precip.; lightning mostly distant
31 May	1441–1622	19	17	Convective cells near radar
11 Jun	1617–2015	20	20	Few convective cells west and northwest
12 Jun	1313–1635	11	9	Line of convective cells passed radar
13 Jul	1412–1842	20	0	High elevation angles in light rain
26 Jul	1351–1805	34	25	Numerous cells mostly southwest and west
15 Aug	1120–1818	12	11	Weak convective line passed radar

Note: Radar operations were conducted also on 8 Apr (1500–1549), 14 May (1147–1322), 19 Jul (1156–1736), 23 Jul (1245–1834), 19 Aug (Hurricane Bob, 0417–1649), and 19 Sep (0806–1320).

LIGHTNING LOCATIONS FROM NATIONWIDE NETWORK

17 May 1991, 1630–1815 EST

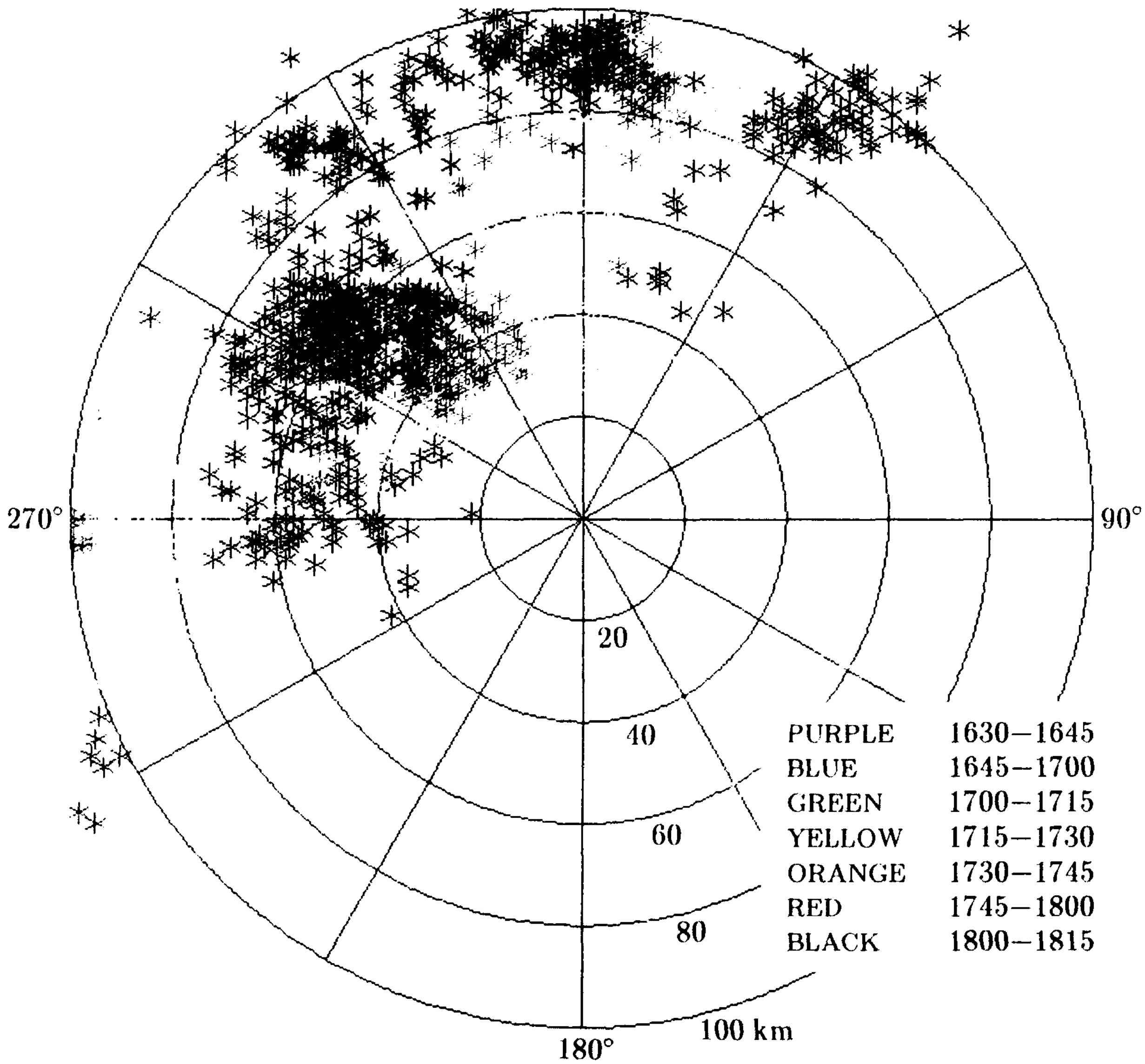

Figure 1. Cloud-to-Ground Lightning, 17 May 1991. Display shows one active cell northwest of the radar between 1630 and 1715 EST (purple through green) and another cell that approached from the west after 1700 EST (green through red). Both of these decreased in intensity as they approached the radar. Lightning locations derived from the nationwide network are displayed relative to the coordinates of the radar site; spatial accuracy, believed to be on the order of a few kilometers, is independent of range from the site.

20 km of the radial increment of the polarimetric observation, that is, within an area of about 1500 km^2. Analysis of the radar data near three of the lightning events observed by radar revealed no discernible changes of the orientation state of the hydrometeors; because of the long range at which these observations were made, we did not examine additional events.

By 1650 the leading edge of the convective line had advanced to about 45 km range, the echo top was just over 12 km altitude, and a distinct area of electrical activity had developed at 40–70 km range between 290 and 325° azimuth. Polarimetric data were recorded from 1650–1658 at an elevation angle of 4° and successive azimuths of 310 and 300° with range gates set between 45 and 105 km. Cloud-to-ground lightning occurred at a rate of about 9 per minute within an area of about 700 km^2 near the radar beam throughout the 8-minute interval, but only three events were recorded in the radar data. None of these events was accompanied by detectable changes in the orientations of hydrometeors.

The segment of the convective line closest to the radar site weakened after 1700. Polarimetric data recorded from 1715–1720 at an azimuth of 320° and an elevation angle of 8° included four lightning events but no associated changes of hydrometeor orientations. Cloud-to-ground lightning between azimuths of 300 and 340° and ranges of 35 to 50 km, in an area of about 400 km^2, occurred at a rate of 8 per minute between 1700 and 1705 but only about 2 per minute during the time of radar data acquisition. Additional polarimetric data were recorded from 1733–1742 at an azimuth of 290° and elevation angle of 4.5° with range gates set between 31 and 91 km. A slight concentration of cloud-to-ground lightning had been noted in the area just prior to 1730, but during the interval of radar data acquisition strikes were occurring at only about 0.8 per minute in an area of about 200 km^2. Seven lightning events were recorded in the radar data, but none of these was accompanied by changes in the hydrometeor orientations.

By 1730 a cell with strong electrical activity was centered about 75 km west of the radar site and approaching at a speed of about 70 km hr^{-1}. The rate of cloud-to-ground lightning was about 6 per minute in an area of about 800 km^2 before 1745. After 1800 the lightning rate decreased rapidly. Polarimetric data were recorded during elevation scans at an azimuth of 270° from 1818–1820 and at an elevation angle of 10° from 1823–1830.

During these times there were only two cloud-to-ground strikes between 240 and 300° azimuth, and only three lightning events were observed by radar, one during the scans and two during the stationary observation. None of these was accompanied by detectable changes of hydrometeor orientations. During the elevation scan a significant propagation effect was noted between 5.5 and 10°, where the radar beam passed through the region of highest reflectivity, which was above 35 dBZ.

While the storm passed overhead, we recorded polarimetric data at vertical incidence from 1833–1850 and recorded seven lightning events. None of these coincided with the two cloud-to-ground strikes within 10 km of the radar during this interval. Two that were analyzed in detail did not reveal any coincident changes of hydrometeor orientations.

The storm moved eastward and maintained a nearly constant azimuth from the radar. Figure 2 shows the radar plan position indicator (PPI) display at 1852, after the storm had passed. Beginning at 1900 we observed the receding storm at an azimuth of 95° and elevation angle of 9° with range gates set between 0.6 and 59.4 km. No cloud-to-ground lightning occurred within 30° of this azimuth from 1900 to 1919, but we observed ten lightning events by radar from 1900 to 1904. The first of these, at 1900:53, was accompanied by the most vivid hydrometeor reorientation that we have yet seen. This observation, shown in Figure 3, indicates a change of electric field spanning an exceptionally large range domain. The lightning is evident in the reflectivity and the CDR in pixels 28–30 in time. It is more readily seen in the CDR (range gates 17–26) than in the reflectivity because the backscatter from the lightning plasma is less masked by hydrometeor backscatter in the transmission channel than in the "main" channel. In range gates 20–42 (range 23.4–49.8 km, height 3.7–7.8 km) for several seconds before the lightning the cross-correlation is between 6 and 48% and the phase is between −90 and +60°; for several seconds after the lightning, the cross-correlation is between 18 and 60% and the phase is between −80 and 0°. Individual range gates show changes of 12–18% (2–3 quantization levels in the image) in cross-correlation and about 40° (2 quantization levels) in phase. Of the other nine events, two were accompanied by slight changes of cross-correlation in 1 or 2 range gates.

At 1904 we began a series of repeated elevation scans between 7 and 11°

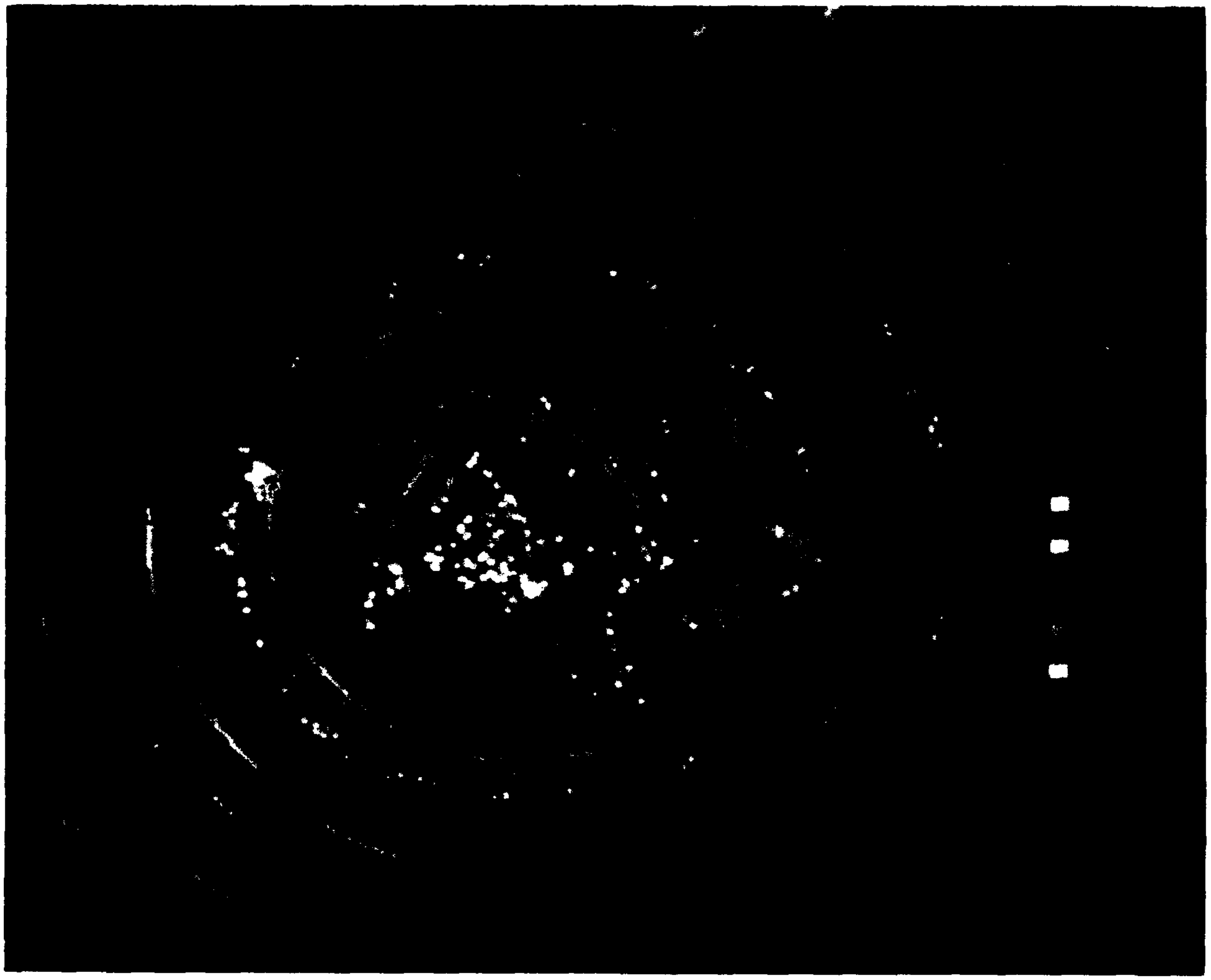

Figure 2. Radar Plan Position Indicator (PPI) Display, 17 May 1991. Range markers are at increments of 16 km. Azimuthal scan at elevation angle of 0.5° at 1852 EST shows line of convective activity crossing the surveillance area. Convective cell 25–45 km due east of the radar was observed subsequently at an azimuth of 94°.

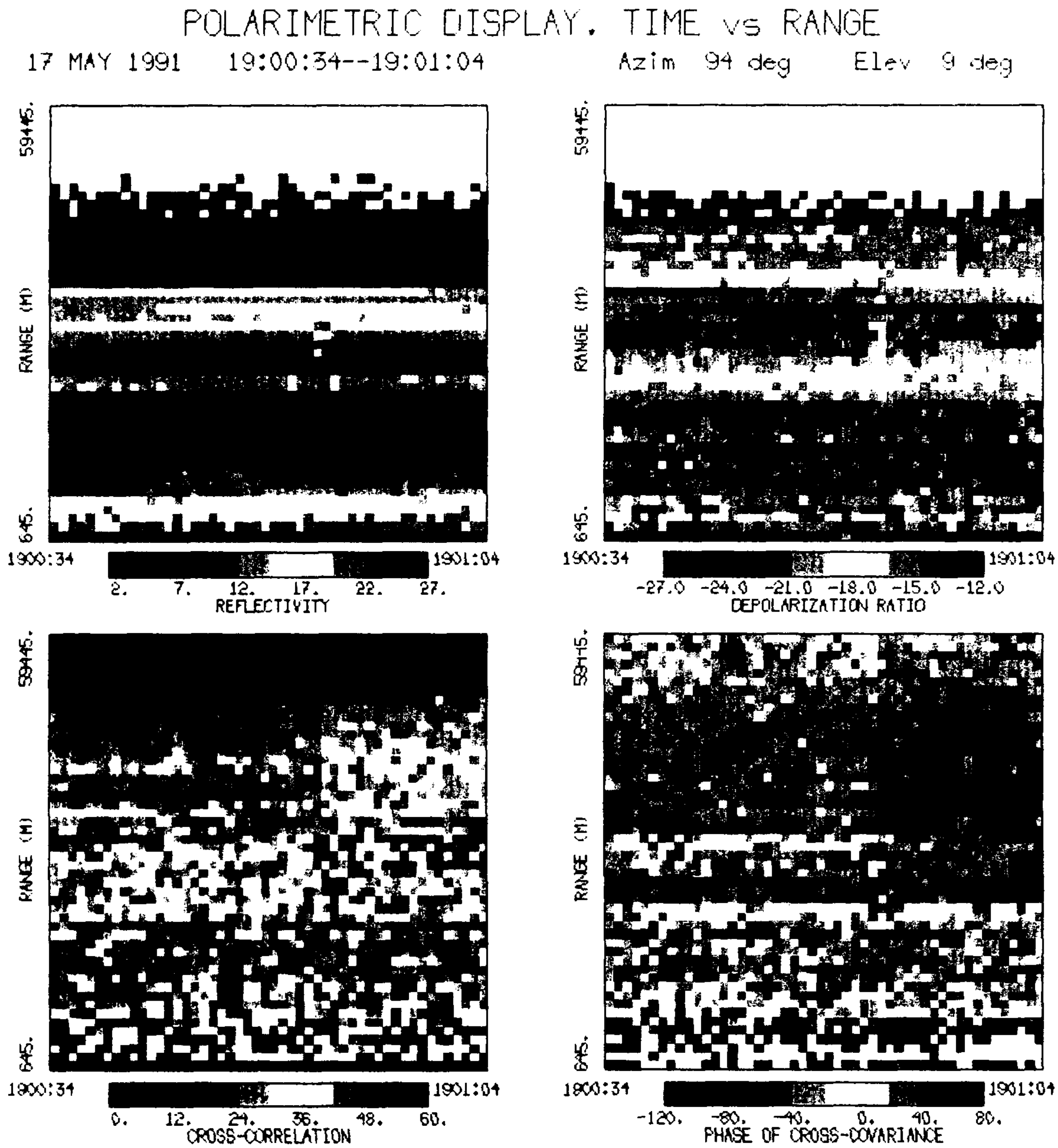

Figure 3. Lightning and Changing Hydrometeor Orientations, 17 May 1991. Antenna was held stationary at 94° azimuth and 9° elevation. Range domain 0.6–59.4 km corresponds to heights of 0.1–9.3 km. Time domain of display is 20 sec. *Upper left:* Reflectivity (dBZ) shows momentary increase due to backscatter from the ionized lightning channel superimposed on the nearly constant hydrometeor backscatter. Duration of lightning channel is about 0.8 sec (two pixels). *Upper right:* Circular depolarization ratio (decibels) exhibits values near zero decibels (exceeding the present color scale) due to the backscatter from lightning, but no discernible change in the hydrometeor backscatter at the time of the lightning. *Lower left:* Cross-correlation of orthogonally polarized signals (per cent) exhibits a marked increase at all ranges between 23 and 50 km (gates 20–42) coincident with the lightning. *Lower right:* Phase of the cross-covariance of orthogonally polarized signals (degrees) exhibits a slight change coincident with the lightning.

in an attempt to glimpse the spatial distribution of hydrometeor reorientations. By this time very few cloud-to-ground strikes were occurring within 60 km of the radar. Strikes were recorded at 1909:09 (183° azimuth, 7 km range), at 1919:46 (80°, 35 km), and 1921:28 (89°, 43 km). We recorded 22 lightning events in the radar data from 1904 to 1927, of which we analyzed 14 in detail. In addition, we analyzed radar data near the times of the latter two cloud-to ground strikes. Of the 16 analyzed events, 9 were accompanied by slight changes of the cross-correlation in spatial domains of a few kilometers in range and a kilometer or less in height within the 4° elevation sector. One event, however, at 1905:00, coincided with a significant change over a large spatial domain. The effects of this event are shown in Figure 4. The upper panels show the cross-correlation derived from downward scans immediately before and after the upward scan during which the lightning echo was observed. The difference of these displays, shown in the lower left, shows that the change was limited to the upper region of the storm. The reflectivity display shown in the lower right reveals the main core at ranges of 31–41 km. The lightning echo is evident in a few pixels, but one should remember that the display reveals only the time of the lightning event and its rangewise extent at that time and does not reveal its full spatial extent.

The observations on 17 May constituted our first major operation of the year and were our first after obtaining near-real-time access to data from the lightning detection network. The electrical activity was generally decreasing throughout the late afternoon and evening, although small concentrations of lightning occurred intermittently. Because of the time delay of a few minutes in our display of the lightning data it was not possible to identify these concentrations immediately or to determine their movement or dissipation while the radar data were being recorded. In retrospect, it is obvious that in some instances the radar azimuth was not optimum or that electrical activity near the radar beam diminished rapidly just before or during the data acquisition. It is remarkable that the most significant changes of hydrometeor orientations coincident with lightning occurred after the cloud-to-ground lightning had nearly ceased.

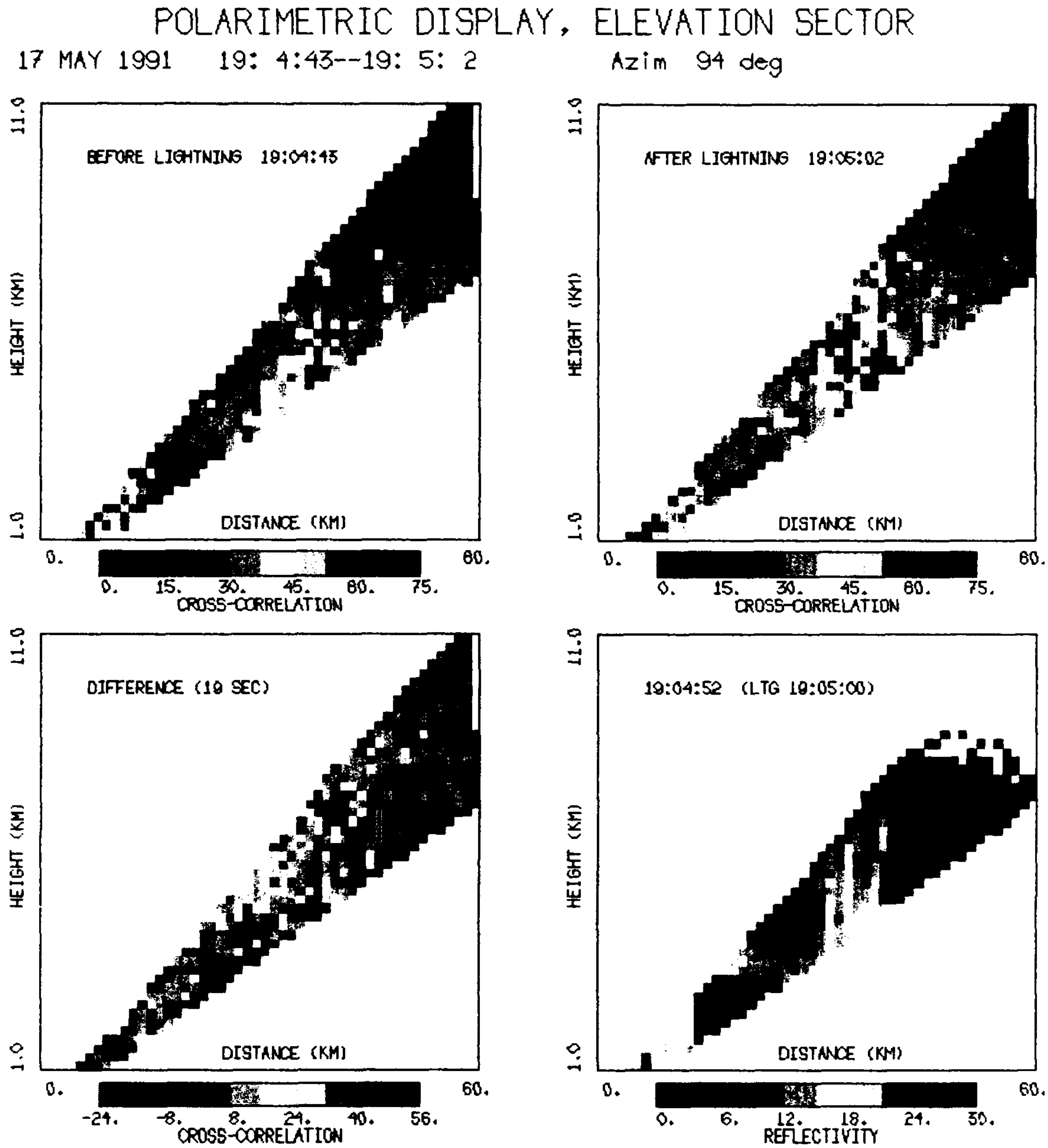

Figure 4. Changing Hydrometeor Orientations in Vertical Section. Antenna was scanning between elevation angles of 7 and 11° at a rate of one full cycle every 18 seconds. *Upper panels:* Cross-correlation (per cent) in successive downward scans before (left) and after (right) the occurrence of lightning in the radar beam reveals an increase in the degree of orientation in the upper part of the sector. *Lower left:* Difference in cross-correlation between the two scans is between 10 and 50% at ranges of 24–38 km (columns 21–32). *Lower right:* Reflectivity measured in the intervening upward scan shows the core of the storm at ranges of 31–40 km (columns 27–33), the melting level at a height of 2.5 km in the stratiform precipitation behind the storm core, and two pixels in which backscatter from the lightning dominates backscatter from hydrometeors.

3.2. 30 May 1991

An area of widespread precipitation developed in the northwest quadrant and expanded as it moved southeastward. Weak electrical activity prior to 1600 EST diminished before the precipitation reached the radar site about 1625. By 1630 a cell had developed about 120–150 km due west. Cloud-to-ground lightning occurred at a rate of about 6 strikes per minute in an area of about 1000 km^2 throughout the period 1700–1800 as the cell moved very slowly southeastward. By 1730 lightning was also occurring infrequently in much of the southwest quadrant beyond 60 km range. Because the nearby lightning activity was infrequent, we judged this not to be an optimum day for observation of electrical effects on hydrometeors. We made only two series of polarimetric observations. The first was from 1754–1801 at an azimuth of 230° and elevation angle of 2.5° with range gates set between 45.6 and 104.4 km. There had been a slight increase of electrical activity at 70–90 km range on this azimuth between 1730 and 1745, but this activity decreased during the time of the polarimetric observation. Two cloud-to-ground strikes occurred within 5° of the radar azimuth at 92 and 95 km range during the 6½-minute obsevation, but 49 occurred in the intense cell within 10° of the radar azimuth and between 110 and 130 km range, that is, 5–25 km beyond the range domain of the polarimetric observation. Seventeen lightning events were observed by the radar, three of which occurred within 10 seconds of a cloud-to-ground strike and several of which were beyond the range of the most distant gate. None of these were accompanied by detectable hydrometeor reorientations.

By 1830 most of the precipitation was in the southern half of the surveillance area, and the intense cell in the southwest was weakening. A second series of polarimetric data was recorded at 1857–1902 at an azimuth of 200° and elevation angle of 2.9° with range gates set between 35 and 93.8 km. By this time, cloud-to-ground lightning activity had decreased sharply in this area; one strike at 195° and 114 km range was the only strike between 180 and 220° azimuth during the 5-minute observation. Six lightning events were detected by radar, one of which occurred 3 seconds before the cloud-to-ground strike. These were all in a cell at 82-88 km range, where the beam was at a height of about 5 km. One of these events was accompanied by slight changes of the CDR (+1 dB) and cross-

correlation (−5%) in two range gates. Four cloud-to-ground strikes occurred between 165 and 180° azimuth during the radar observation, indicating that the center of electrical activity had moved eastward and that the azimuth of the observation was not optimum.

This day did not offer good observational opportunity, as the level of electrical activity was low and most of this activity was distant from the radar. More timely access to the lightning data might have aided the polarimetric data acquisition.

3.3. 31 May 1991

Several convective cells of weak to moderate reflectivity developed within 100 km of the radar during the afternoon. Between 1400 and 1415 EST a cell near 290° azimuth and 30–60 km range produced 12 cloud-to-ground strikes in an area of about 250 km^2; it subsequently weakened, and an attempt to observe it from 1441–1446 at an elevation angle of 8° with range gates set between 17.4 and 76.2 km yielded only two lightning events in the radar data and no coincident hydrometeor reorientations. After 1445 electrical activity appeared near 200° azimuth and 30–40 km range; between 1500 and 1545 cloud-to-ground strikes occurred at a rate of 1.6 per minute in an area of about 400 km^2. A polarimetric observation from 1523–1530 at an azimuth of 190° and successive elevation angles of 8 and 10° with range gates set between 25.8 and 55.2 km yielded five lightning events in the radar data. During this interval there were eight cloud-to-ground strikes within 10 km of the radar beam segment; four of these were followed within 20 sec by a lightning event in the radar data. Three of the five lightning events observed by radar coincided with significant changes of phase in a few gates. The quantitative details of these observations are presented in Table 2. While it is of interest that these occurred within a few minutes of one another, their wide spatial and temporal distribution makes it difficult to establish any continuity among them.

After 1545 the rate of cloud-to-ground strikes decreased rapidly. A final polarimetric observation was made from 1547–1554 at an azimuth of 180° and elevation angle of 7° with range gates set between 29.9 and 59.3 km.

Ten lightning events were observed by radar, and two cloud-to-ground strikes were recorded during this interval, one of which followed by 5 sec an event observed by radar. Subsequent analysis revealed slight changes of the polarimetric quantities accompanying five of the observed events during the first three minutes of the observation. In four of these events the phase decreased by about 10°, in one event the phase increased by 20°, and in three events the cross-correlation decreased by about 5% from initial values of 25–35%. The noisiness of the phase, due in part to the small values of cross-correlation, limits the quantitative meaning of these measurements. The occurrence of relatively frequent lightning events in the radar data while the cloud-to-ground strike rate was very low is similar to the situation of 17 May. As in some of the observations of that day, we observed hydrometeor reorientations early in this observational period, but in this case the effects were of much smaller magnitude and spatial extent.

Electrical activity occurred close to the radar, and numerous lightning events were detected during three periods of polarimetric data acquisition. The first and third of these series were in areas where the rate of cloud-to-ground lightning decreased sharply near the beginning of the observation, and the observed changes of hydrometeor orientations were slight at most. The second observation was in an area that maintained its electrical activity, and significant changes of mean canting angle accompanied three of five lightning events.

Table 2. Hydrometeor Reorientations Observed on 31 May 1991. Range domain of observation was 25.8–55.2 km). "NC" denotes no change of the quantity.

Event	Time (EST)	Elev. (deg)	Range (km)	Cross-correl. (%) Before	After	Phase of cross-covariance Before	After
1	15:23:16	8°	43.8–46.2	5–30	NC	−50 to 0°	−30 to +20°
4	15:27:38	10°	43.8–44.4	20–30	NC	30 to 80°	−30 to +30°
5	15:28:39	10°	36.0–38.4	10–50	NC	40 to 80°	20 to 60°

3.4. 11 June 1991

Several convective cells developed to the west and northwest of the radar by 1630 EST and moved eastward at about 50 km hr^{-1} across the northern half of the surveillance area during the following 3 hr. Cloud-to-ground lightning was widespread beyond 75 km range to the northwest by 1700; subsequently lightning was more concentrated in a few areas. Figure 5 shows lightning recorded by the network from 1800–1945. By 1800 a cell to the northwest was producing cloud-to-ground lightning at a rate of 5 per minute in an area of about 800 km^2. We recorded polarimetric data while observing this cell from 1803–1812 at an azimuth of 320° and successive elevation angles of 11, 12, and 13° with range gates set between 14.9 and 44.3 km. Fifteen lightning events were detected by radar during the first 10 minutes of the interval and none thereafter, although cloud-to-ground lightning continued. Two of these events coincided with distinct but moderate changes of cross-correlation in 10 or more range gates; one is shown in Figure 6. Six events coincided with slight changes of cross-correlation or phase, generally in only a few range gates.

We observed this cell again from 1834–1840 at azimuths of 345 and 350° and elevation angle of 11.8° with range gates set between 19.8 and 49.2 km. Three lightning events were detected by radar during the interval but no cloud-to-ground strikes were recorded within 15 km of the beam segment. The third of these events coincided with small (5%) increases of the cross-correlation spanning about 15 km in range. The region of electrical activity appeared to have moved more rapidly eastward, as the cloud-to-ground strikes during the interval were at 30–70 km range and azimuths of 20–40°, at a rate of about 7 per minute.

Another cell, initially west of the radar, showed increased electrical activity after 1830 and passed within 20 km south of the radar about 1900. From 1850–1905 cloud-to-ground strikes occurred at a rate of 5 per minute in an area of 200 km^2; thereafter the rate was about 3 per minute. We observed this cell from 1911–1916 at an azimuth of 109° and elevation angles of 19 and 25° with range gates set between 16.2 and 30.9 km. Two lightning events were recorded by radar during the first 2 minutes and none thereafter; six cloud-to-ground strikes occurred in an area of about 200 km^2

LIGHTNING LOCATIONS FROM NATIONWIDE NETWORK

11 June 1991, 1800–1945 EST

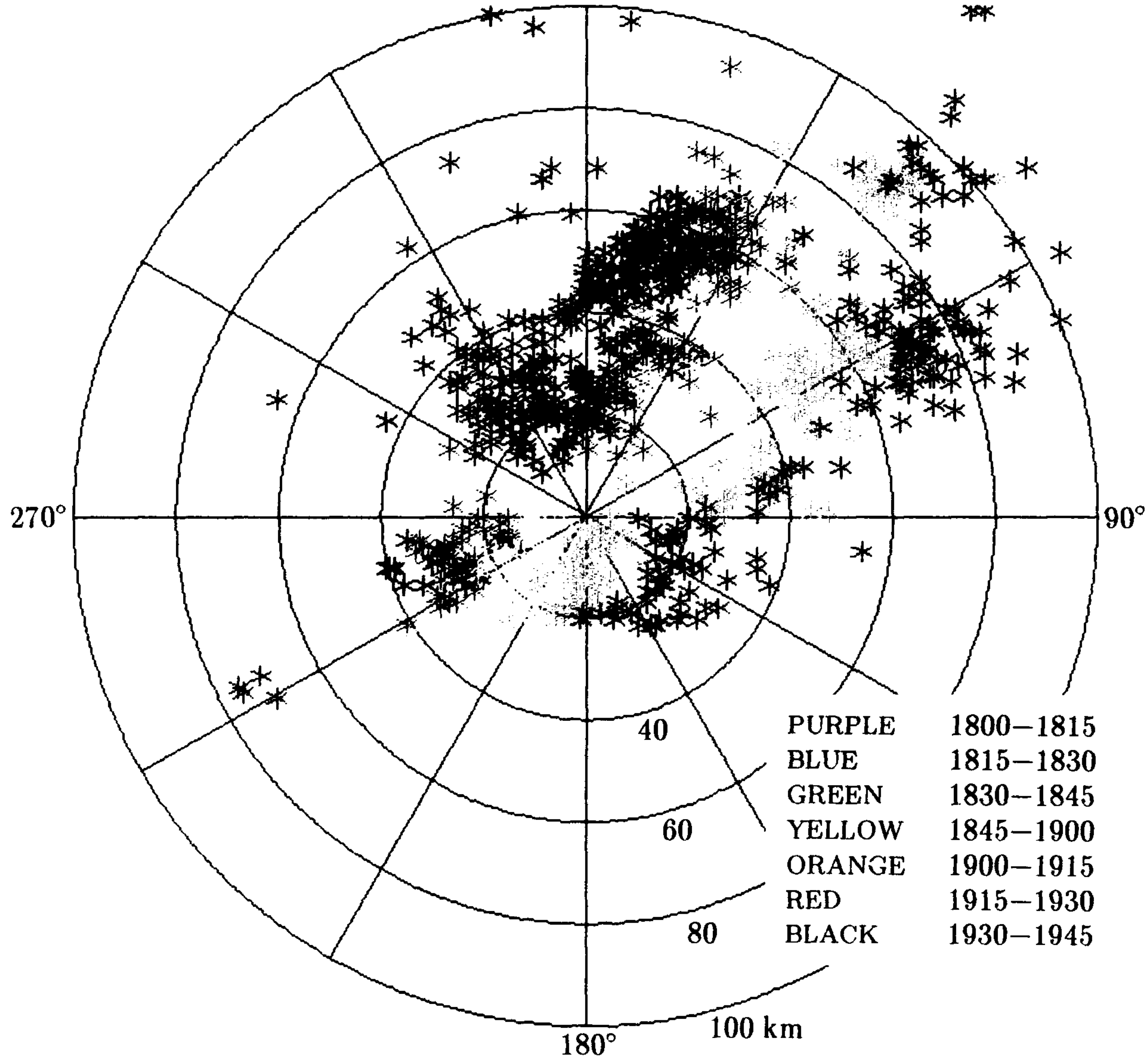

Figure 5. Cloud-to-Ground Lightning, 11 June 1991. Display shows one cell that passed north of the radar about 1830 EST (blue and green) and another cell that passed closely to the south about 1900 (yellow and orange).

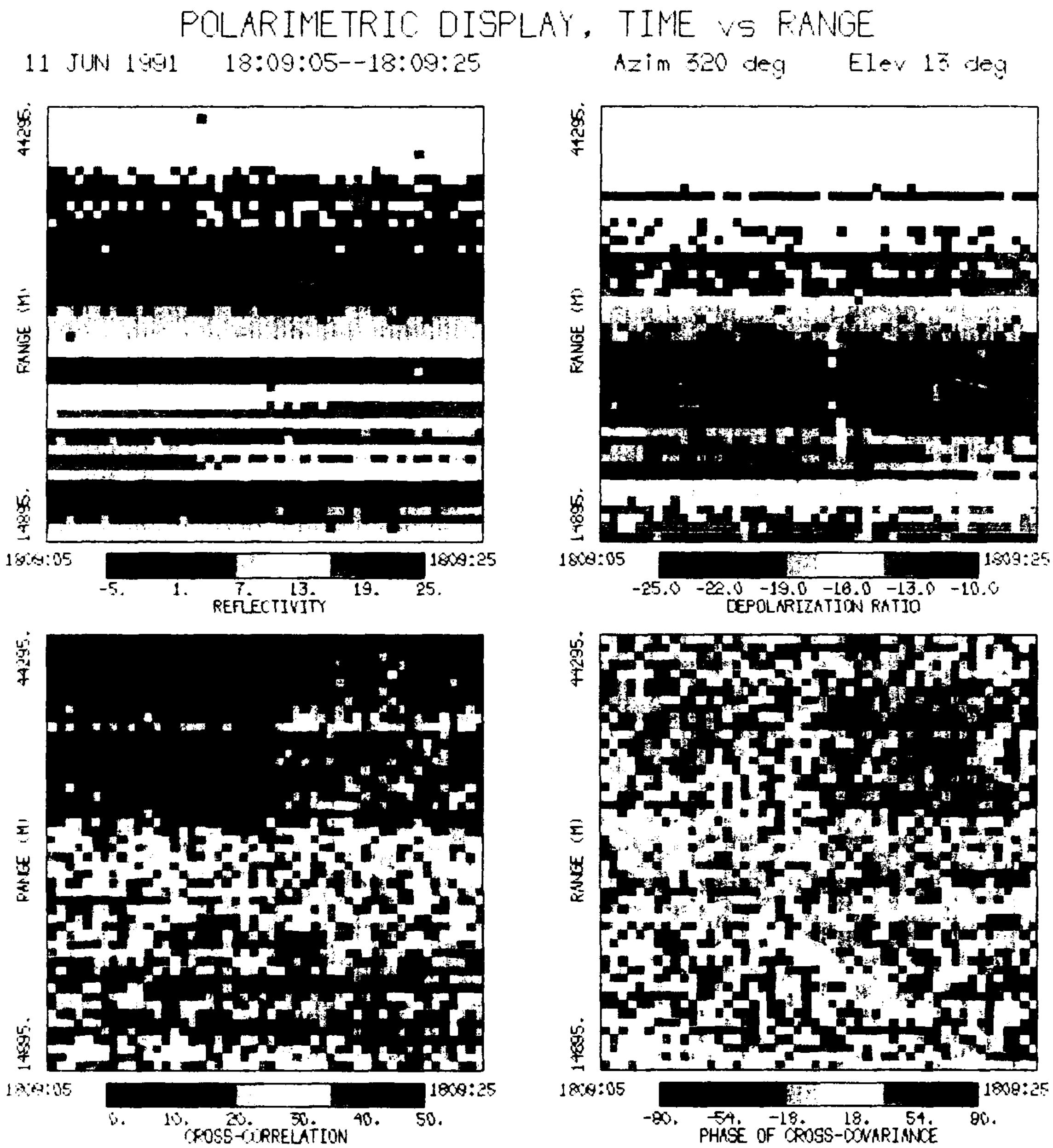

Figure 6. Lightning and Changing Hydrometeor Orientations, 11 June 1991. Antenna was stationary at 320° azimuth and 13° elevation. Range domain 14.9–44.3 km corresponds to heights of 3.4–10 km. Time domain of display is 20 sec. Displayed quantities are identical to those in Figure 3. Lightning at 1809:16 (columns 27 and 28) extends nearly 8 km in range and spans the region of highest reflectivity. Within that region the cross-correlation is mostly 15–40% and is unchanged at the time of the lightning. In the region of weaker reflectivity beyond 33 km range (gate 30, 7.4 km height) the cross-correlation is initially 0–15% and increases suddenly to 10–25% at the time of the lightning. The phase, initially very noisy, attains values between −50 and 0° after the lightning.

near the beam segment. The first event coincided with a slight change of the phase, and the second, which occurred within a few seconds of a cloud-to-ground strike, coincided with a 35° change of phase. The cross-correlation was generally small (10–50%) and exhibited no changes coincident with the lightning. In this case it appears that we pointed the beam too far ahead of the center of electrical activity; most of the lightning during this interval occurred at azimuths of 120–190° and ranges of 8–22 km.

The cell that passed north of the radar offered a potentially good observational opportunity, as it maintained a relatively high level of electrical activity. Changes of CDR, cross-correlation, and phase coincided with several lightning events, but these were generally of small magnitude and exhibited no continuity. Our second observation of the same cell after an interval of about 20 min was only minimally successful, due apparently to the delay in our access to the lightning data. In the third observation the rapid azimuthal movement of the cell at very close range was an additional factor in our failure to observe more than two lightning events by radar.

3.5. 12 June 1991

A line of convective cells passed through the surveillance area during the afternoon. The leading edge of the line advanced from the northwest at about 40 km hr^{-1}, reaching the radar site about 1445 EST. Movement of individual cells within the line was nearly due east. Cloud-to-ground lightning, shown in Figure 7, was concentrated just behind the leading edge of the line. By 1400 there were two principal concentrations of lightning, one 40–70 km to the north and one 80–120 km to the west. We chose not to observe the northern cell because of its distance and rapid azimuthal movement; this may have been a mistake because that cell produced lightning at a rate of 3–4 strikes per minute in an area of 300 km^2 between 1420 and 1430 and continued to be active for more than an hour thereafter. The western cell moved eastward at about 75 km hr^{-1} and crossed the radar site about 1515. We observed this cell from 1500–1511 at azimuths of 235, 230, and 245° and elevation angle of 16° with range gates set initially between 5 and 34.4 km and between 5 and 19.7 km during the last 2½

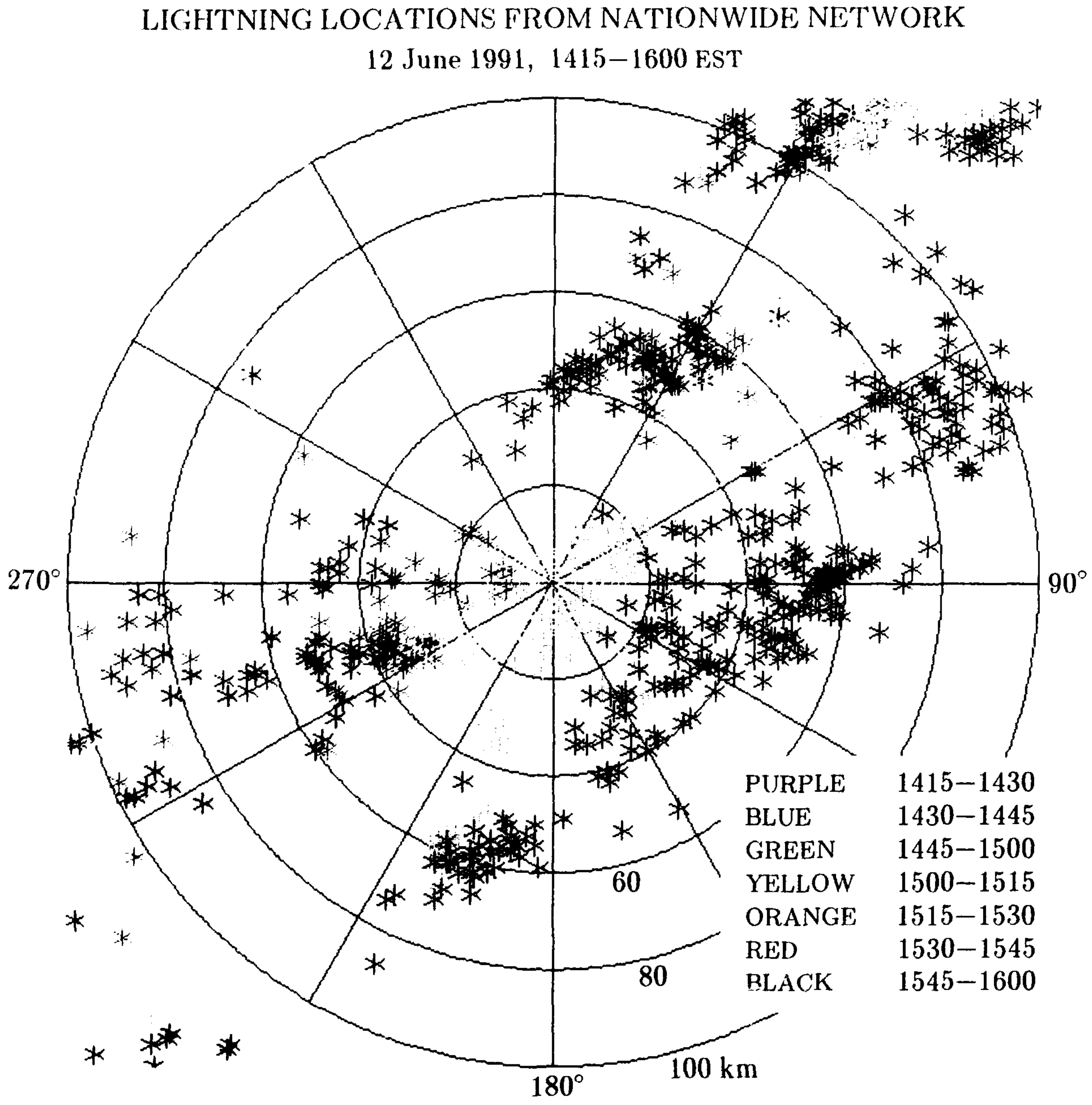

Figure 7. Cloud-to-Ground Lightning, 12 June 1991. Display shows one cell that passed 40 km north of the radar about 1415 EST, a second cell that intensified to the west about 1445 (green) and crossed the radar site about 1515 (yellow and orange), and a third cell that was most active about 60 km to the south between 1515 and 1545 (orange and red).

minutes. Cloud-to-ground strikes occurred at a rate of about 3 per minute in an area of 500 km^2 during the observation; ten lightning events were detected by radar, three of which coincided with cloud-to-ground strikes. With one exception, which is shown in Figure 8, none of the lightning events recorded in the radar data were associated with detectable changes of hydrometeor orientations. In Figure 8 the lightning echo at 1505:32, spanning four range gates, coincided with a cloud-to-ground strike at 234° azimuth and 21 km from the radar. The lightning associated with the large changes of CDR and cross-correlation at 1505:43 is barely identifiable at ranges of 15.8 and 17.6 km (gates 19 and 22); it was not identified on the A-scope during the radar operation. We noted several occasions when the CDR changed by ± 2 dB or the cross-correlation changed by $\pm 10\%$ in time increments of 10 sec or less that did not coincide with either a cloud-to-ground strike or a lightning event detected by radar.

After 1515 we observed this cell repeatedly in elevation scans and in a pointing mode for about 30 min as it moved eastward. Cloud-to-ground lightning continued at a rate of 3 strikes per minute in an area of 500 km^2 and increased to 6 strikes per minute 40–60 km to the east after 1550. By this time we were observing a cell to the southeast, where the line was closer to the radar but less active electrically. We failed to detect lightning in any of these radar observations and did not record additional polarimetric data.

This case should have provided a good opportunity to observe electrical effects on hydrometeor orientations, because there was a moderate level of electrical activity in a cell close to the radar. Our failure to observe orientation effects in nearly all instances emphasizes both the complexity of the phenomenon and the need for accurate and timely electrical data during radar operations.

3.6. 26 July 1991

A line of small cells, extending from about 60 km south of the radar to 100 km southwest, developed about 1400 EST. Individual cells moved toward the northeast at about 35 km hr^{-1}, and the line expanded during the ensuing 2 hours to fill much of the southwest quadrant, while more

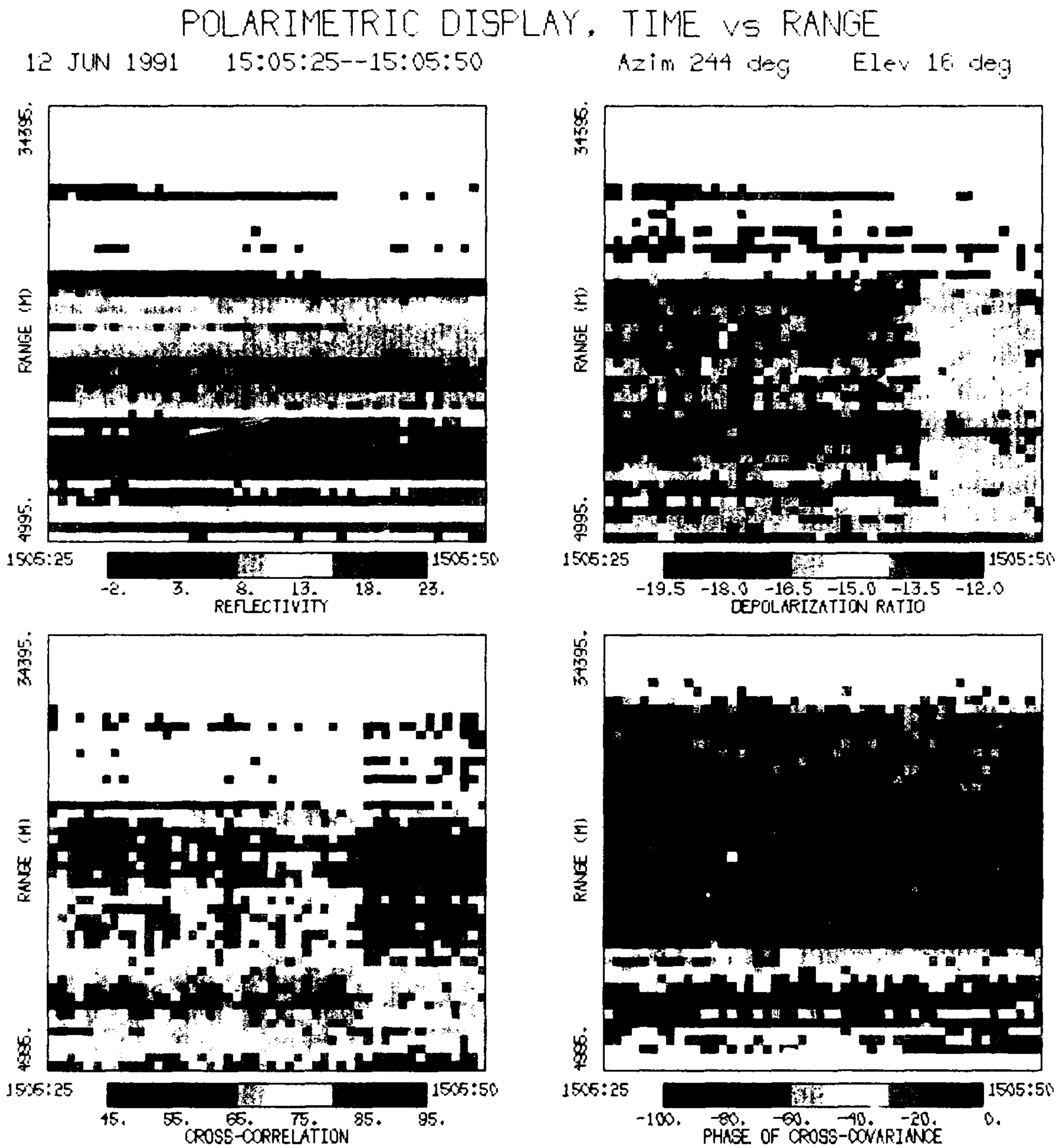

Figure 8. Lightning and Changing Hydrometeor Orientations, 12 June 1991. Antenna was stationary at 245° azimuth and 16° elevation. Range domain 5.0–34.4 km corresponds to heights of 1.4–9.5 km. Time domain of display is 25 sec. Displayed quantities are identical to those in Figures 3 and 6. High reflectivity and low cross-correlation near 10 km range (gate 9) are associated with the melting layer at an altitude of 2.8 km. Lightning at 1505:32 (columns 14 and 15) is accompanied by only slight changes in the cross-correlation and phase. Lightning at 1505:43 (barely discernible in columns 36 and 37) coincides with significant changes in CDR (+1 dB) and cross-correlation (+5 to 10%) in a wide range domain.

scattered precipitation developed in the northwest quadrant. Cloud-to-ground lightning activity was generally slight, except for a few cells that intermittently produced more significant electrical activity. By 1440 one of these cells was about 50 km south of the radar. As this cell moved northeastward during the following 1½ hours and passed within 35 km of the radar at 1530, we observed it repeatedly in elevation scans and in a pointing mode, with the radar beam intersecting the cell at 6–8 km altitude above its core. Cloud-to-ground lightning occurred at 5–6 strikes per minute in an area of 200 km^2 from 1510–1535 and continued at 1–2 strikes per minute until 1605. We detected very few lightning events by radar and therefore did not record any polarimetric data.

After 1630, when that cell had moved to the east of the radar and had weakened, other cells were developing within 60 km south and southwest of the radar. We observed three other areas where cloud-to-ground lightning occurred. In each of these observations we recorded polarimetric data and observed lightning events by radar. The first series of polarimetric data was recorded from 1700–1704 at an azimuth of 214° and elevation angle of 10° with range gates set between 20.4 and 35.1 km. During the interval, five cloud-to-ground strikes occurred within 10 km of the radar beam segment, that is, within an area of about 600 km^2; three lightning events were detected by radar, each of which occurred within 9 sec of a cloud-to-ground strike. The second series was recorded from 1714–1720 at successive azimuths of 155, 152, and 150° and elevation angle of 11.6° with the same range gate settings as before. Three lightning events were detected by radar, and one cloud-to-ground strike occurred about 1 min after the last event detected by radar. In neither of these observations were any of the lightning events accompanied by detectable changes of hydrometeor orientations. In each observation the cross-correlation was less than 50% throughout the observed range domain.

The third series was recorded from 1726–1736 at an azimuth of 115° and elevation angle of 12° with the same range gate settings as before. Only one cloud-to-ground strike occurred near the radar beam segment. During the first 2 minutes of observation no lightning events were detected, but thereafter 14 events were detected during 6½ minutes. The first 11 of these lightning events were accompanied by no detectable changes of hydrometeor orientations. Of the last three, two coincided with significant

changes of cross-correlation and one with a significant change of phase. The quantitative details of these observations are presented in Table 3.

The situation on this day is difficult to interpret. In particular, we are puzzled by our failure to detect significant lightning activity by radar in a storm that produced significant cloud-to-ground lightning for about 1 hr. With that exception, the electrical activity near the radar was generally low. The cell observed in the third series moved northeastward, and from 1753–1810 it produced 9 strikes in an area of about 250 km^2 centered about 45 km east-northeast of the radar. It is possible that the orientation effects we observed near the end of the third series were related to the subsequent increase of lightning in this cell.

Table 3. Hydrometeor Reorientations Observed on 26 July 1991. Range domain of observation was 20.4–35.1 km. Highest reflectivity was between 27 and 34 km, where radar beam was 5.6 to 7.1 km above ground level. Observed changes of cross-correlation and phase occurred between 31 and 34 km. "NC" denotes no change of the quantity.

Event	Time (EST)	Cross-correl. (%) Before	Cross-correl. (%) After	Phase of cross-covariance Before	Phase of cross-covariance After
12	17:33:21	15–35	5–25	−120 to −40°	NC
13	17:34:02	5–30	NC	−100 to −30°	−130 to −60°
14	17:34:30	15–35	10–25	−120 to −45°	−120 to −30°

3.7. 15 August 1991

A line of convective cells developed about 90 km northwest of the radar about 1500 EST and moved southeastward at about 35 km hr^{-1} during the following 3½ hours. Individual cells moved toward the east-northeast at speeds of 40–50 km hr^{-1}. With the exception of one strong cell 120–150 km to the north that produced cloud-to-ground lightning for about 1½ hr at a rate that exceeded 2 per minute for one 15-minute period in an area of about 200 km^2, the electrical activity was weak and intermittent. Polarimetric data were recorded from 1554–1600 at an azimuth of 306° and

elevation angle of 3.5° with range gates set between 69.5 and 84.2 km. These coordinates corresponded to a region where cloud-to-ground lightning had occurred at a rate of 0.4–0.7 per minute in an area of 500 km^2 between 1500 and 1545; this activity decreased rapidly thereafter. Nine lightning events were recorded by the radar during the observation; one of these coincided with a 30° change of phase in a single range gate.

The most significant cloud-to-ground lightning within 100 km of the radar occurred from 1615–1640 when about 1 strike per minute occurred in an area of about 200 km^2 centered near 290° azimuth and 50 km range. Particular cells were observed in a pointing mode at 1634–1647 and 1709–1712 as the convective line approached the radar, but few lightning events were observed and no polarimetric data were recorded. A more lengthy series of observations was made from 1723–1743 at azimuths of 246–334°, when the leading edge of the line was less than 25 km from the radar. A second series of polarimetric data was recorded from 1738–1743 at successive azimuths of 260, 264, and 266° and elevation angle of 7° with range gates set initially between 27.6 and 57 km and subsequently between 18.9 and 48.3 km. Cloud-to-ground lightning had almost ceased by this time, however; no strikes were recorded during the interval of data recording. Two lightning events were recorded by radar, one of which was accompanied by a 6-dB increase of CDR in a single range gate.

This day did not offer a good observational opportunity because the cells were of moderate intensity at most and electrical activity was generally weak and decreasing as the convective line approached the radar.

4. SUMMARY

During the spring and summer of 1991 we recorded polarimetric data on nine days when thunderstorms were within our surveillance area. On four of these days (31 May, 11 June, 12 June, and 26 July) cells with significant electrical activity passed close to the radar, providing what seem in retrospect to have been the best opportunities to observe the effects of changing electric fields on the orientations of hydrometeors. We observed electrically active regions for intervals of 4 to 28 minutes' duration and

observed 176 occurrences of lightning in the radar beam. We analyzed 143 of these in detail by examining the circular depolarization ratio (CDR), the cross-correlation, and the phase of the cross-covariance in time intervals of 20–30 sec spanning the times at which lightning was observed by radar. Twelve of these events, from five days, [17 May (2), 31 May (3), 11 June (3), 12 June (1), 26 July (3)] coincided with significant changes of hydrometeor orientations, evident in one or more of the computed quantities. These include changes exceeding 1 dB in CDR, 5% in cross-correlation, or 10° in phase. About 30 other lightning events coincided with smaller changes in the computed quantities, some of which occurred in only a few range gates. Our observations reveal that the change of CDR associated with a rapidly changing electric field is usually no more than 1–2 dB and in many instances there is no detectable change of CDR. The cross-correlation and the phase of the cross-covariance seem to be more reliable indicators of the changing electric field, although in many instances the changes of these quantities are also small. We have observed changes up to 50% in cross-correlation and 40° in phase. The latter corresponds to a change of 20° in the mean apparent canting angle. The spatial extent of these changes varies from a few kilometers to about 20 km. In a few cases we observed three or more reorientations during a few minutes, but some, including the two most vivid events, were unique within a time interval of several minutes despite the repeated occurrence of lightning in the radar beam. Thus, while we have demonstrated that the changes of orientation are detectable at a radar wavelength of 11 cm, we have not observed the cyclical changes of the measurable quantities that have been observed elsewhere by radars of shorter wavelength.[3, 5]

We have not observed changes of orientation of hydrometeors at ranges beyond about 70 km. It is likely that the the effects we are attempting to observe are increasingly obscured by spatial averaging as the size of the illuminated volume increases with range. At longer ranges the radar is less capable of detecting the smallest hydrometeors that are most responsive to the electric field. We have also found that wide spacing of the range gates, that is, at an interval of 1.2 km, is not generally desirable. Although our most vivid observation of changing orientations was made with this spacing, the associated lack of spatial continuity is generally disadvantageous.

Several factors contribute to our limited success in detecting changes of

hydrometeor orientations in clouds. First, our radar wavelength is more than three times that of the radar used by Krehbiel[3] and six times that of the radar used by Hendry and McCormick.[5] Our radar therefore receives relatively more backscatter from larger hydrometeors that are less responsive to the ambient electric field in clouds. Because of the difference in backscatter characteristics we expect to see changes in the polarimetric quantities that are smaller than the changes observed with radars of shorter wavelength. Second, we experienced difficulty in determining the polarimetric phase accurately. The relative noisiness of the phase of the cross-covariance is due at least in part to a high level of phase noise in the coherent receivers, particularly near their saturation power level. We attempted to alleviate this problem by attenuating the signals manually during the polarimetric observations. The receivers were replaced in December 1991 by more stable amplitude-limiting receivers, which are expected to yield much less noisy measurements. Third, our observational strategy may have been deficient. We usually aimed the radar beam to intersect an electrically active cell between 6 and 8 km altitude, well above the melting level but low enough that the hydrometeor backscatter in each channel was well above the receiver noise level. Other investigators of these effects have generally observed storms at 8–10 km altitudes, where the ice particles are smaller and hence more responsive to the electric field. Because of our dependence on detecting lightning channels in the radar beam as indicators of changing electric fields, our observations were further constrained. Krehbiel operates other instrumentation to detect lightning and only occasionally detects lightning channels in his radar beam. Hendry rarely observed them, although the short wavelength of his radar may have precluded detection of lightning in all but the most tenuous of meteorological backscatter media.

We are continuing these observations through the spring and summer of 1992 to refine our experimental procedures and increase our data base. Our approach will differ in several ways from that of 1991, as a result of the experiences described above. We have improved our access to data from the lightning detection network, so that we can now display lightning locations as recent as one minute old. This capability will aid us in the initial selection of features to observe, the tracking of those features while polarimetric data are being recorded, and the early recognition of sudden

decreases of electrical activity. We should also be able to follow more precisely storms that are moving rapidly in azimuth at close range. We have begun to use an electric field change sensor, also known as a "slow antenna," which was under construction during the summer of 1991. This device senses sudden changes of the ambient electric field due to the occurrence of lightning, either in-cloud or cloud-to-ground. It provides an additional indication of the occurrence of lightning, which can be used as a guide to the analysis of the polarimetric data. In conducting the radar observations we aim to achieve greater temporal continuity by observing particular cells repeatedly as long as they exhibit a significant level of electrical activity. The 1991 observations were deficient in this respect. Finally, we plan to investigate more fully the spatial structure and variability of the orientation effects by repeated scans of small sectors of elevation or azimuth. These observations should also provide a basis for development of techniques for mapping electrical characteristics of storms.

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